# Operational Amplifiers

## ECE 321: Electronics II

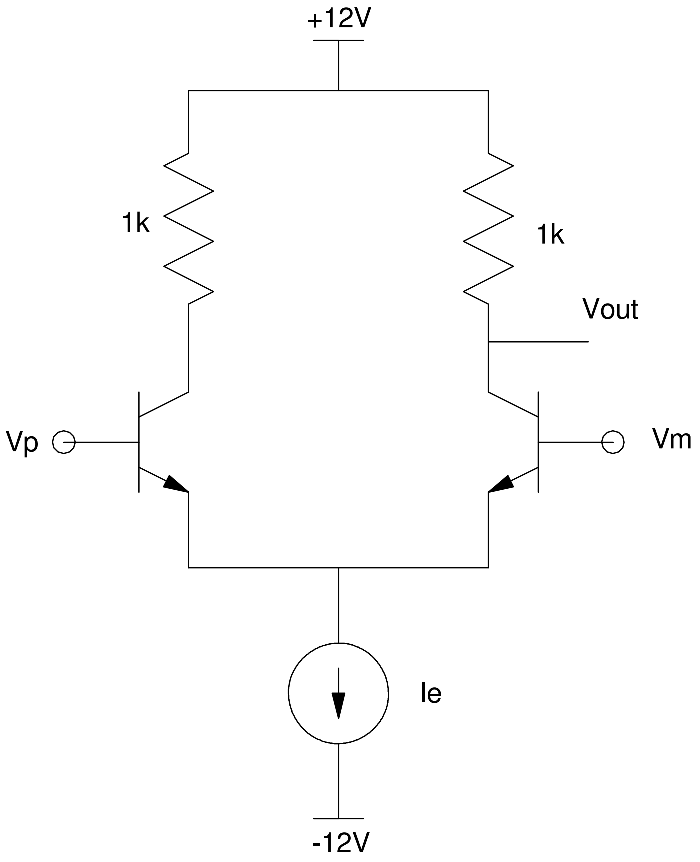
### Lecture #1

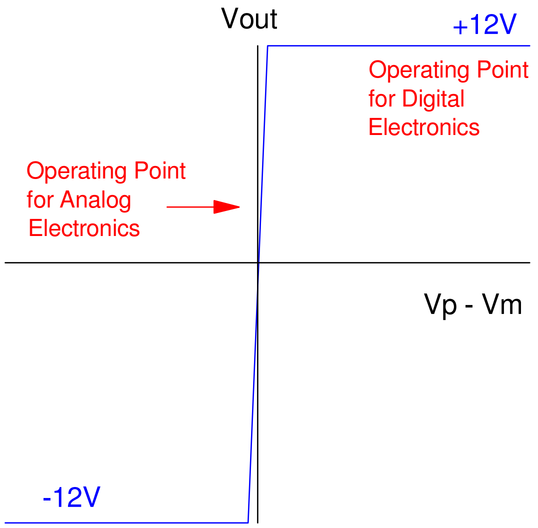
Please visit Bison Academy for corresponding
lecture notes, homework sets, and solutions

# Operational Amplifiers

Operational Amplifiers (Op-Amps) are high gain differential amplifiers.

The heart is emitter-coupled logic:



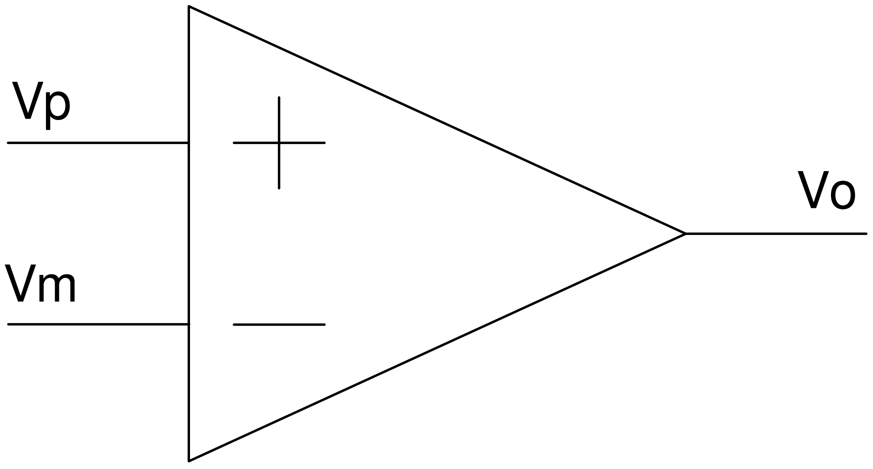


# Op-Amp Symbol

Model:

$$V_o \approx k(V^+ - V^-)$$

where k is a large number.

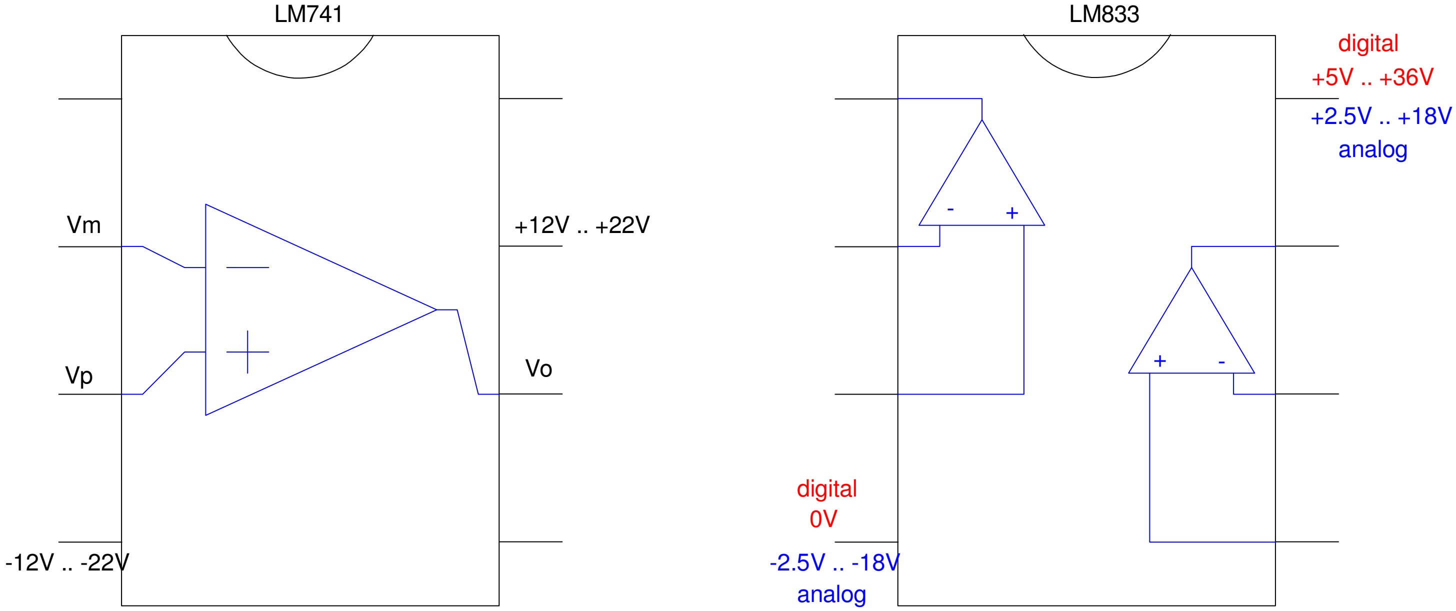


Symbol for an operational amplifier (op-amp)

# Packaging:

Op-Amps usually come in two packages:

- A single op-amp per package (left), or
- Two op-amps per package



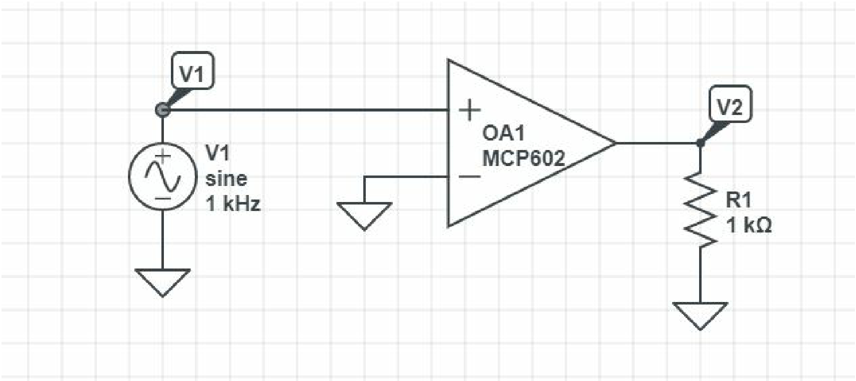
Pin Layout for two common op-amps: LM741 and LM833 / MCP602
The LM833 and MCP602 work for both digital electronics and analog electronics.

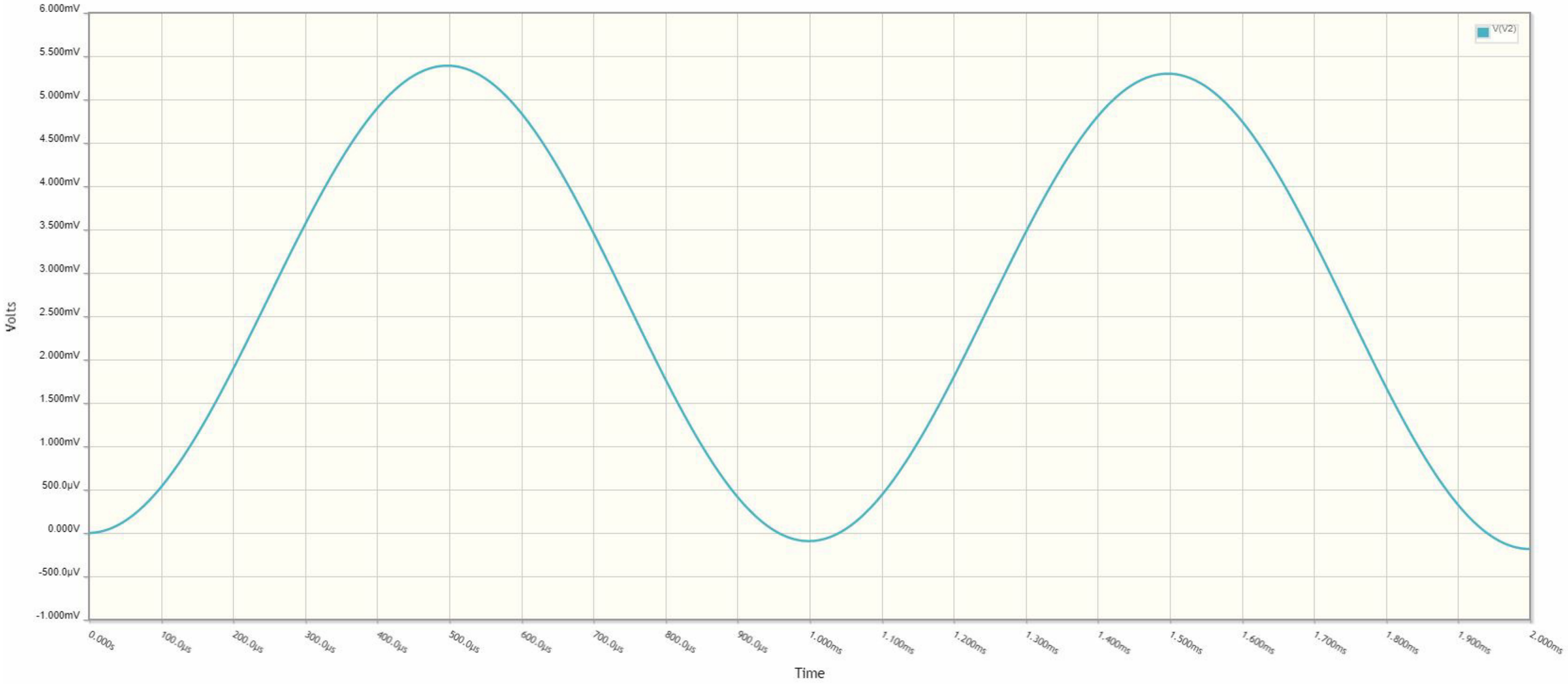
# Data Sheets:

| | LM741 | MCP602 | LM833 | Ideal |
|---|---|---|---|---|
| Input Resistance | 2M Ohms | 1G Ohm | 1G Ohm | infinite |
| Current Out (max) | 25mA | 50mA | 50mA | infinite |
| Operating Voltage | +/- 12V .. +/- 22V | 3V to 6V | +/- 2.5V to 15V | any |
| Differential Mode Gain | 200,000 | 500,000 | 310,000 | infinite |
| Common Mode Rejection Ratio | 90dB | 90dB | 100dB | 0 |
| Slew Rate | 0.5 V/us | 2.3 V/us | 7 V/us | infinite |
| Gain Bandwidth Product | 1.5MHz | 2.8MHz | 15MHz | infinite |
| Price (qty 100) | $0.35 | $0.48 | $0.52 | - |

# Differential Gain (CircuitLab)

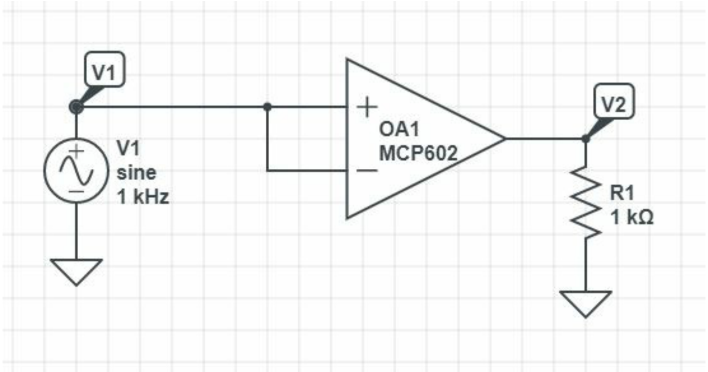
- V1 = 1uVp
- V2 = 5.5Vp
- Gain = 5,500,000

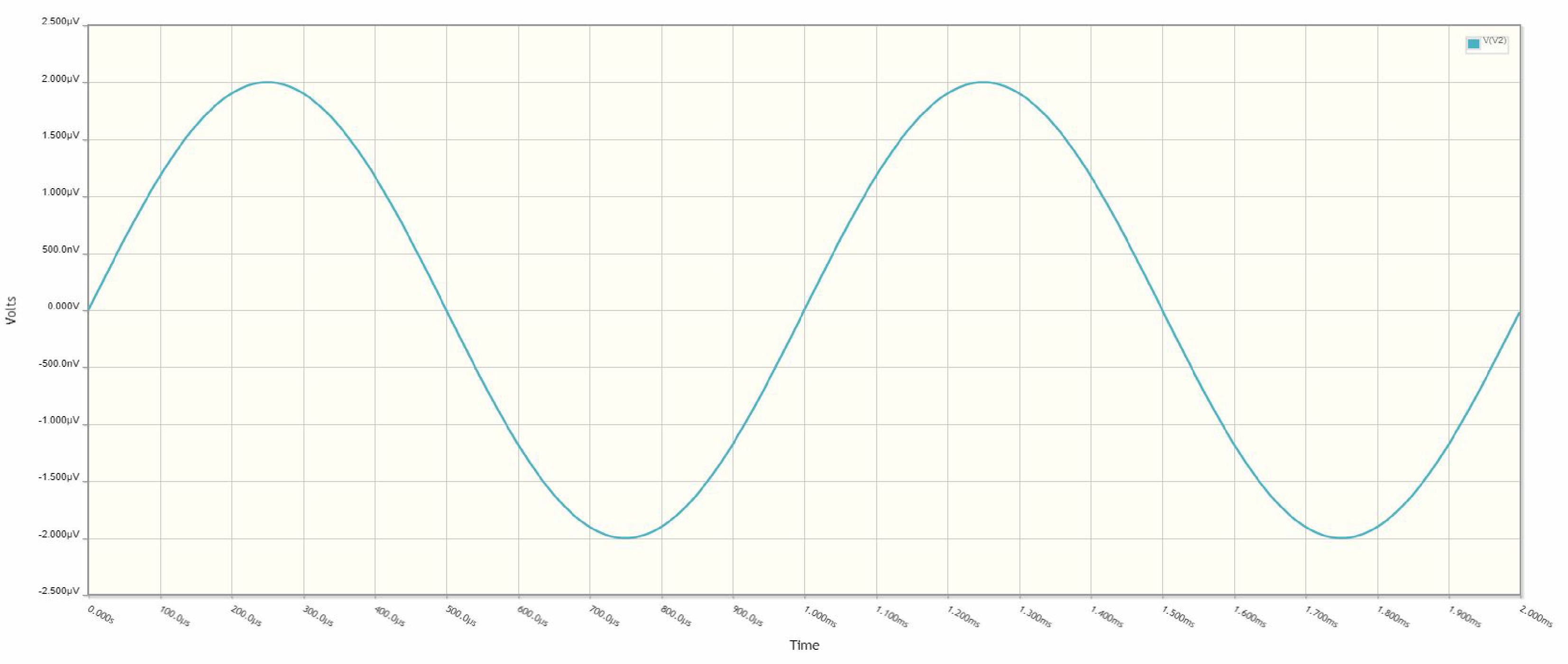




# Common Mode Gain (CircuitLab)

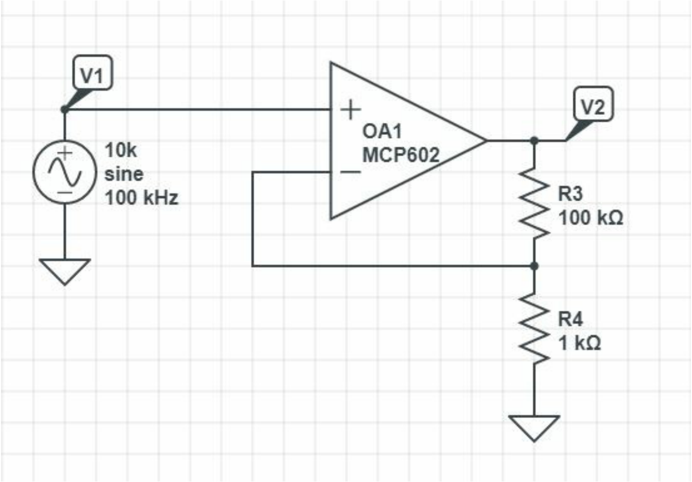
- V1 = 1Vp
- V2 = 2uVp
- Common Mode Gain = 0.000 002

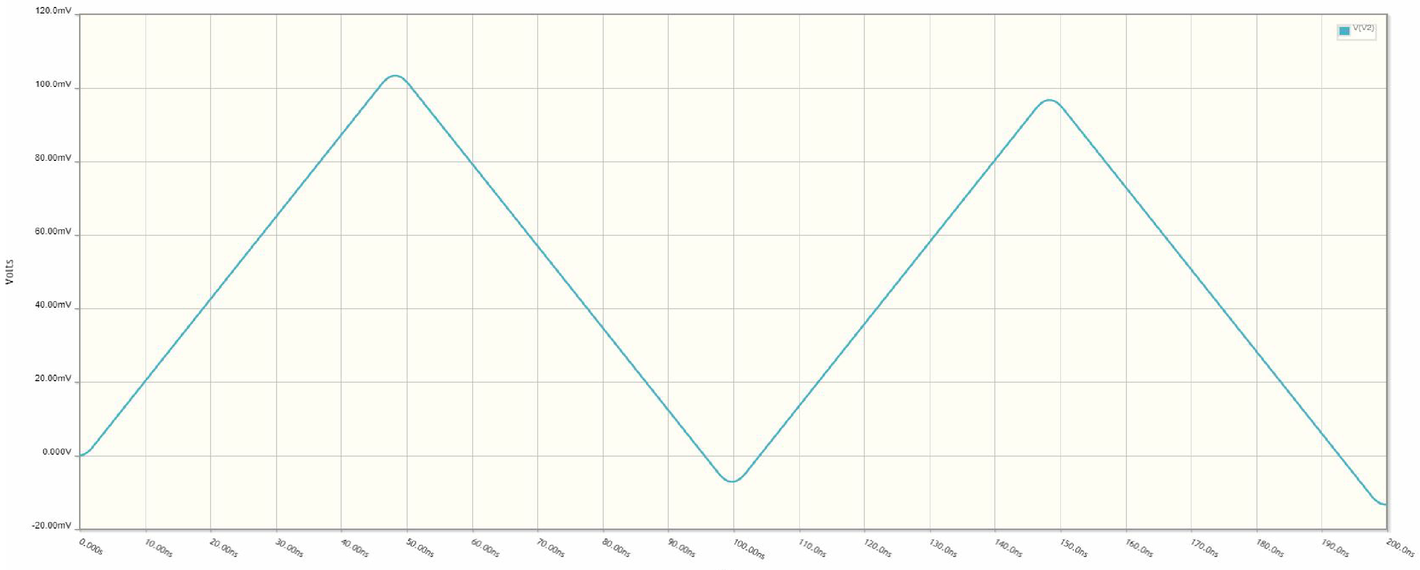




# Slew Rate (CircuitLab)

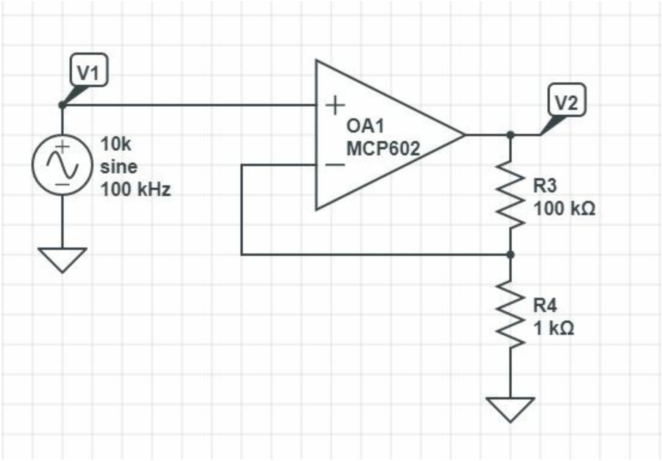
- V1 = 1Vp, 100kHz sine wave
- V2 = triangle wave
- Slope = 2.3e6 V/s (Slew Rate)

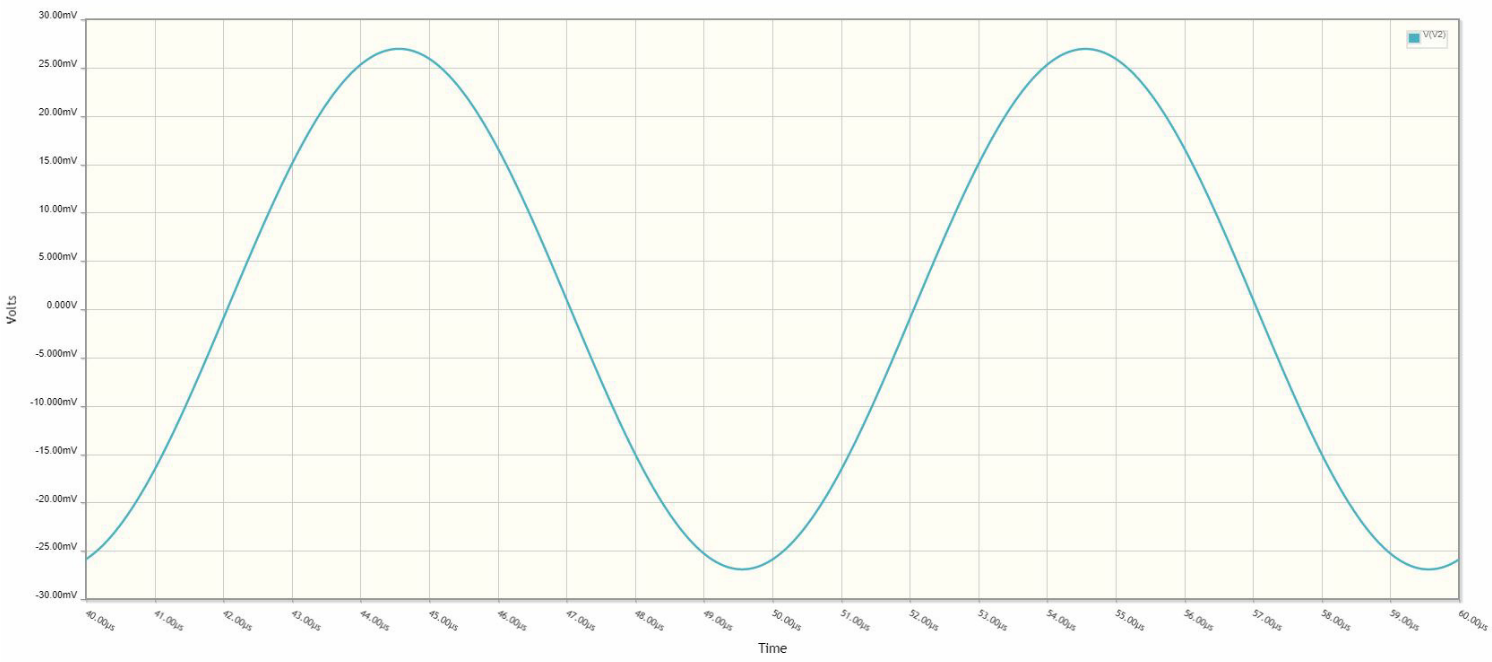




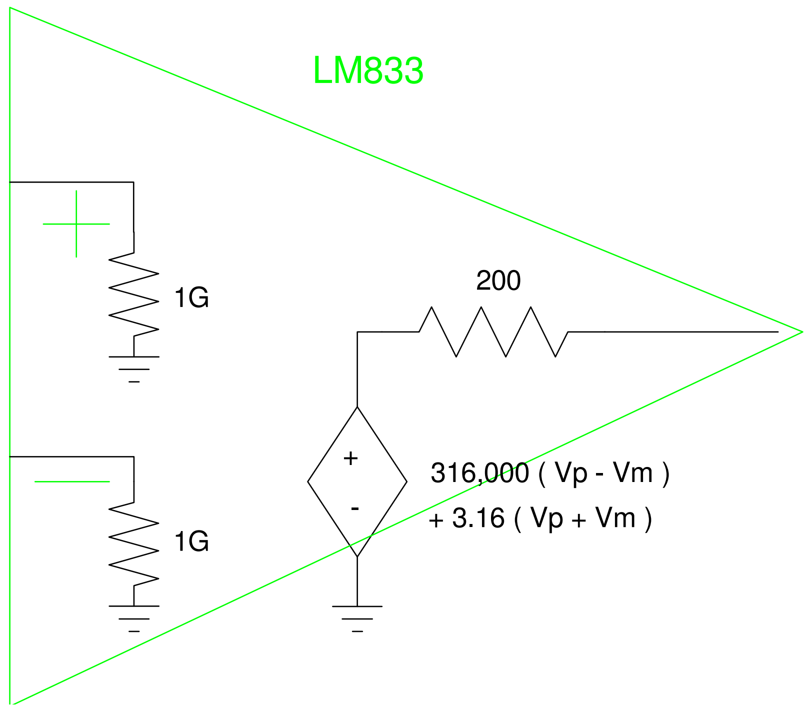
# Gain-Bandwidth Product

- V1 = 1mVp, 100kHz
- V2 = 101mVp, 100kHz (ideally)
- V2 = 28mVp, 100kHz (actual)
- (28)*(100kHz) = 2.8e6 = GPW



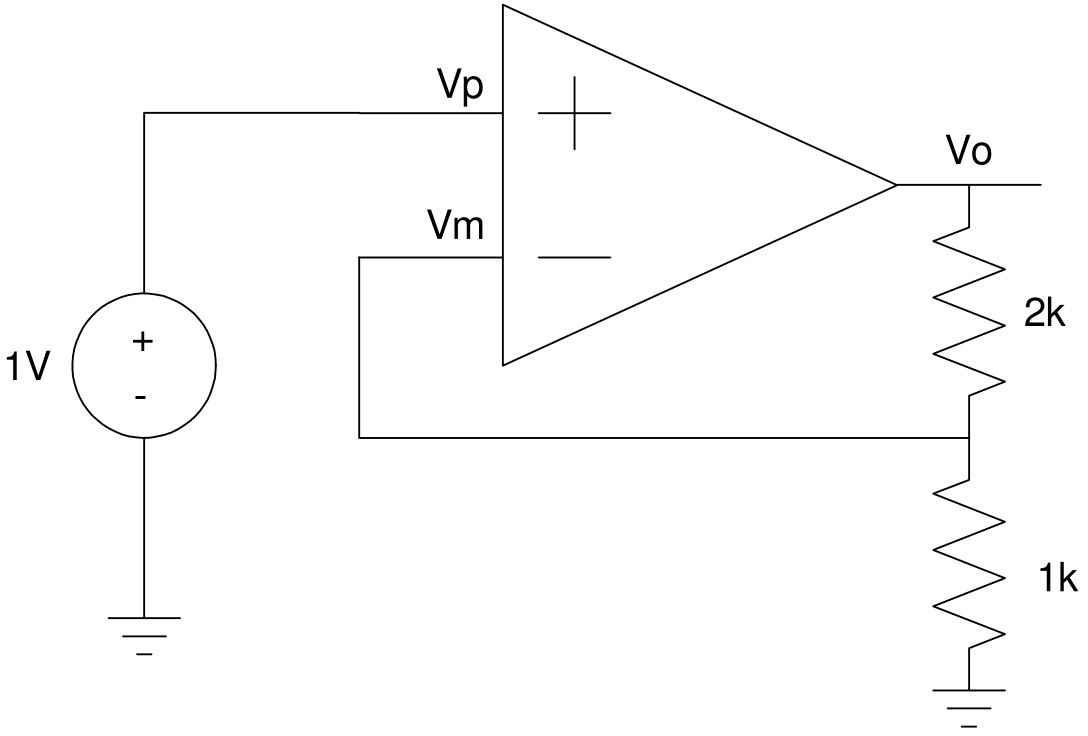


# Translation: LM833



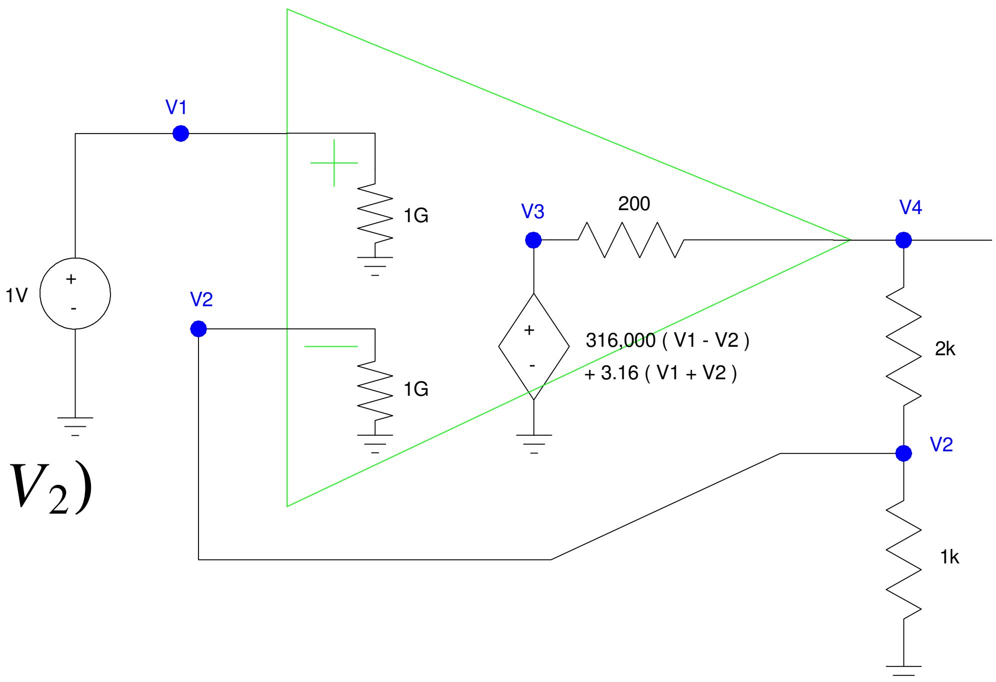
Circuit Model for an LM833.

# Example: Determine the voltages



# Case 1: LM833 Op-Amp

- Very similar to an MCP602



Node equations:

$$V_1 = 1$$

$$\left(\frac{V_2}{1G}\right) + \left(\frac{V_2 - V_4}{2k}\right) + \left(\frac{V_2}{1k}\right) = 0$$

$$V_3 = 316,000(V_1 - V_2) + 3.16(V_1 + V_2)$$

$$\left(\frac{V_4 - V_3}{200}\right) + \left(\frac{V_4 - V_2}{2000}\right) = 0$$

Solve in Matlab:

```
V1     1.
V2     0.9999899
V3     3.1999698
V4     2.9999716
```

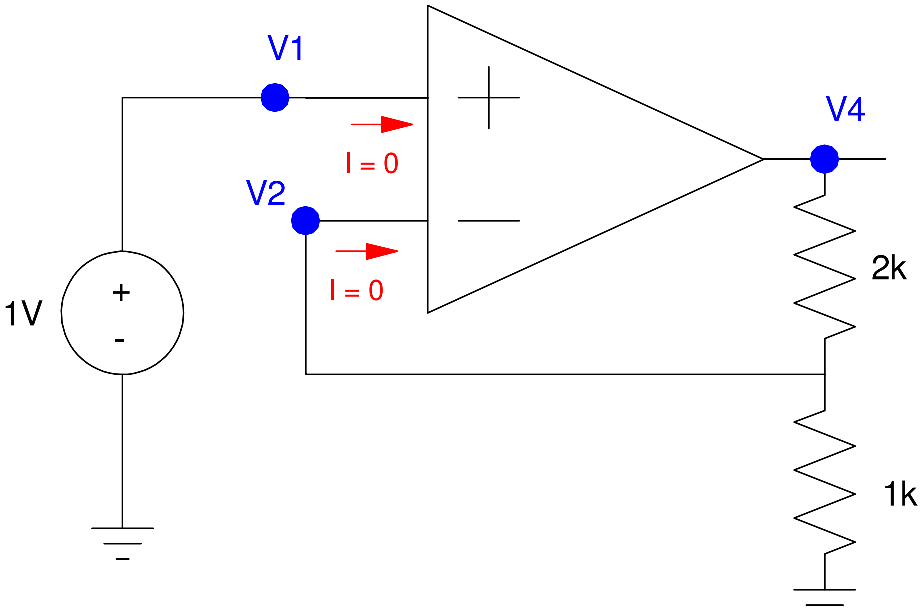
# Case 2:  Ideal Op-Amp

Node equations

$$V_1 = 1$$

$$V_1 = V_2$$

$$\left(\frac{V_2}{1k}\right) + \left(\frac{V_2 - V_4}{2k}\right) = 0$$



Solve

```
        Ideal OpAmp    LM833
 V1     1.             1.
 V2     1.             0.9999899
 V3     n/a            3.1999698
 V4     3.000000       2.9999716
```

# Ideal Op-Amp Model:

- The results are almost identical.
- It's a *lot* easier to use the ideal op-amp model.
- If you use a different op-amp, the results will be about the same.

*note: "about" means*

- *You keep impedances less than 10M Ohms (so you can ignore the 1G input impedance), and*
- *You keep impedances more than 100 Ohms (you draw less than 50mA)*

Likewise, from here on, we'll be assuming ideal op-amps.

# Voltage Nodes with Op-Amps

Node equation at Vo (assuming negative feedback):

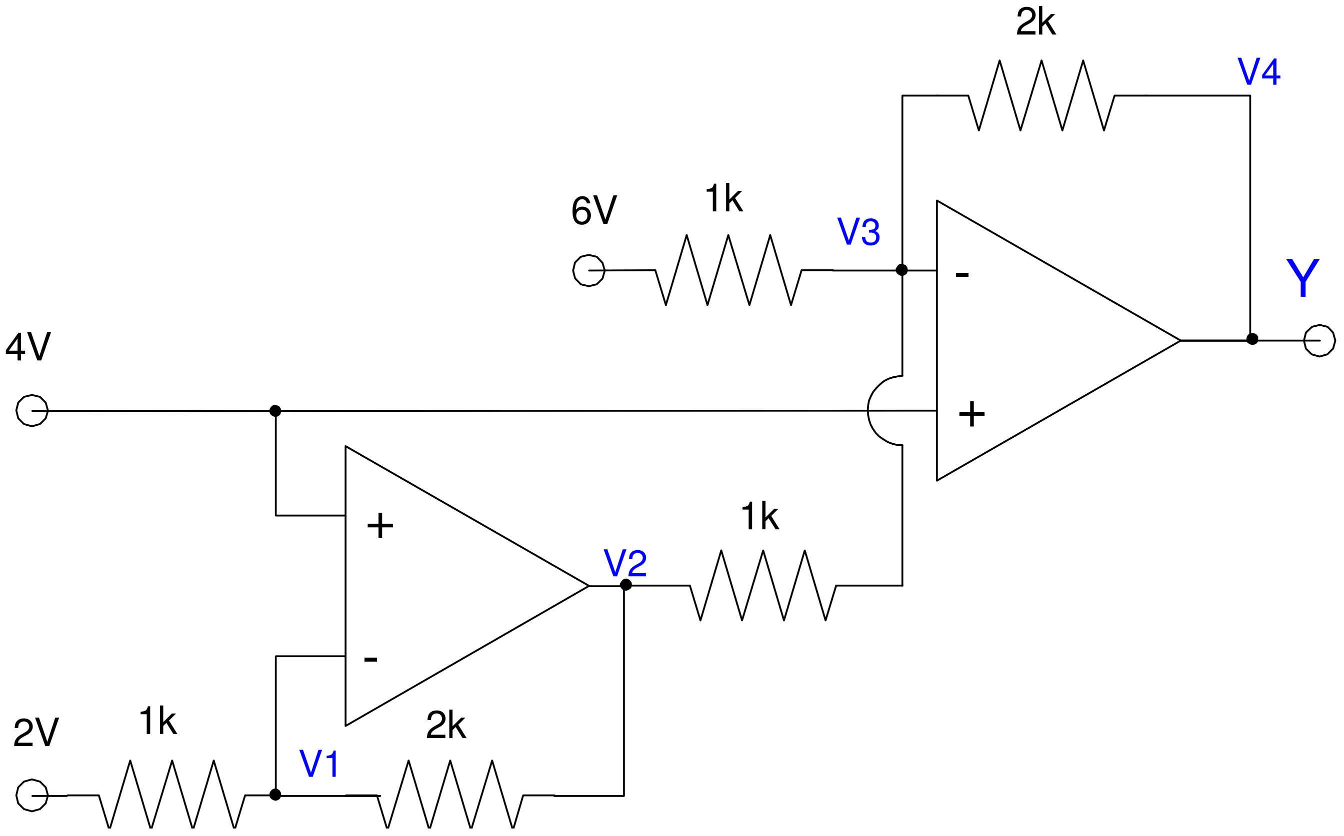
$$V_p = V_m$$

You do this for two reasons:

- (1) If you have negative feedback (i.e. are analyzing an amplifier as opposed to a Schmitt trigger), the high gain will force Vm to be close to Vp. Otherwise, the output would rail at the power supply.
- (2) You can't write the voltage node equation at Vo. The op-amp is an active device and will source or sink as much current as needed to force Vm to match Vp. If you try to write the voltage node equation at Vo, the current from the op-amp is "as much as needed." That doesn't help when writing voltage node equations.

# Example 1:  Write the voltage node equations:

- 4 equations for 4 unknowns
- (handout problem #1)



# Solution: (Take 1)

Vp = Vm

$$V_1 = 4$$

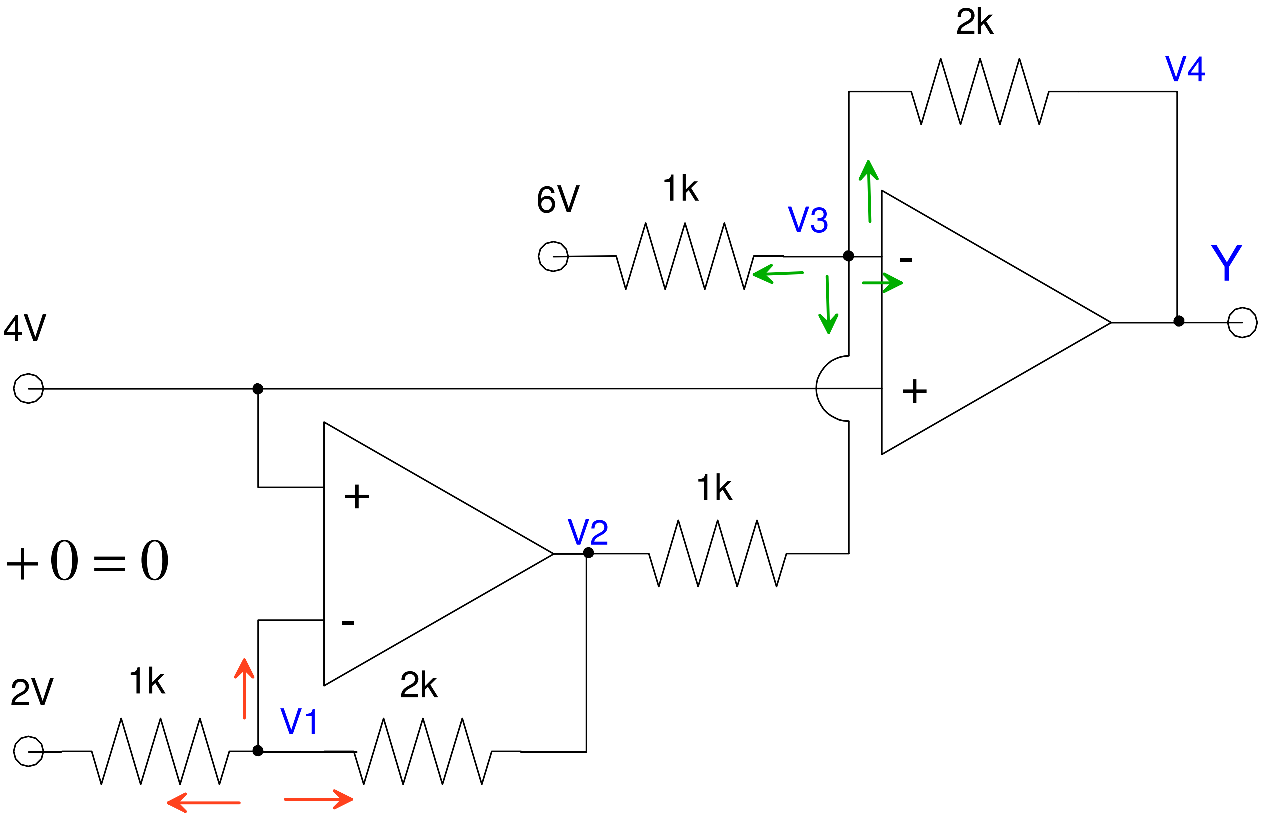
$$V_3 = 4$$

Node V1 (red)

$$\left(\frac{V_1 - 2}{1k}\right) + 0 + \left(\frac{V_1 - V_2}{2k}\right) = 0$$

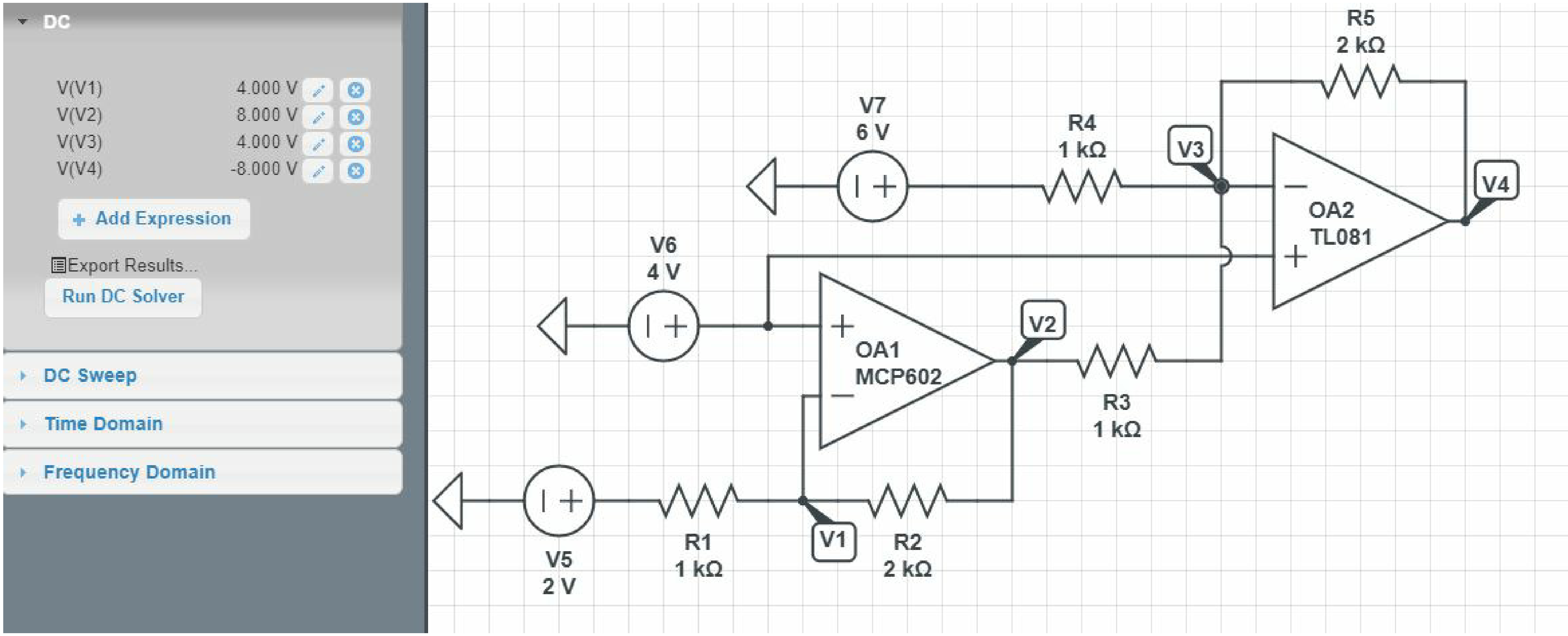
Node V3 (green)

$$\left(\frac{V_3 - V_2}{1k}\right) + \left(\frac{V_3 - 6V}{1k}\right) + \left(\frac{V_3 - V_4}{2k}\right) + 0 = 0$$



# Check in CircuitLab

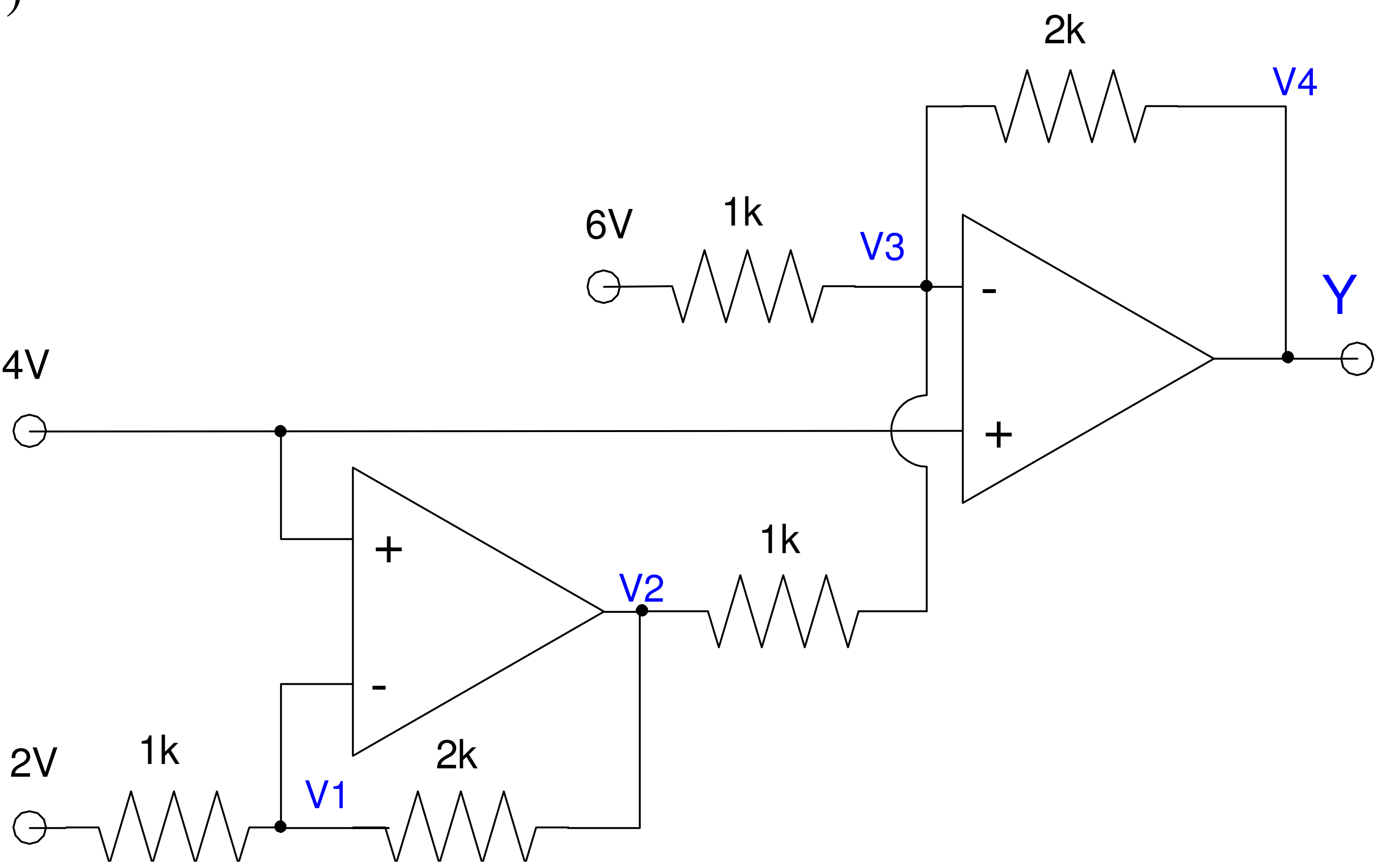
- Same answer



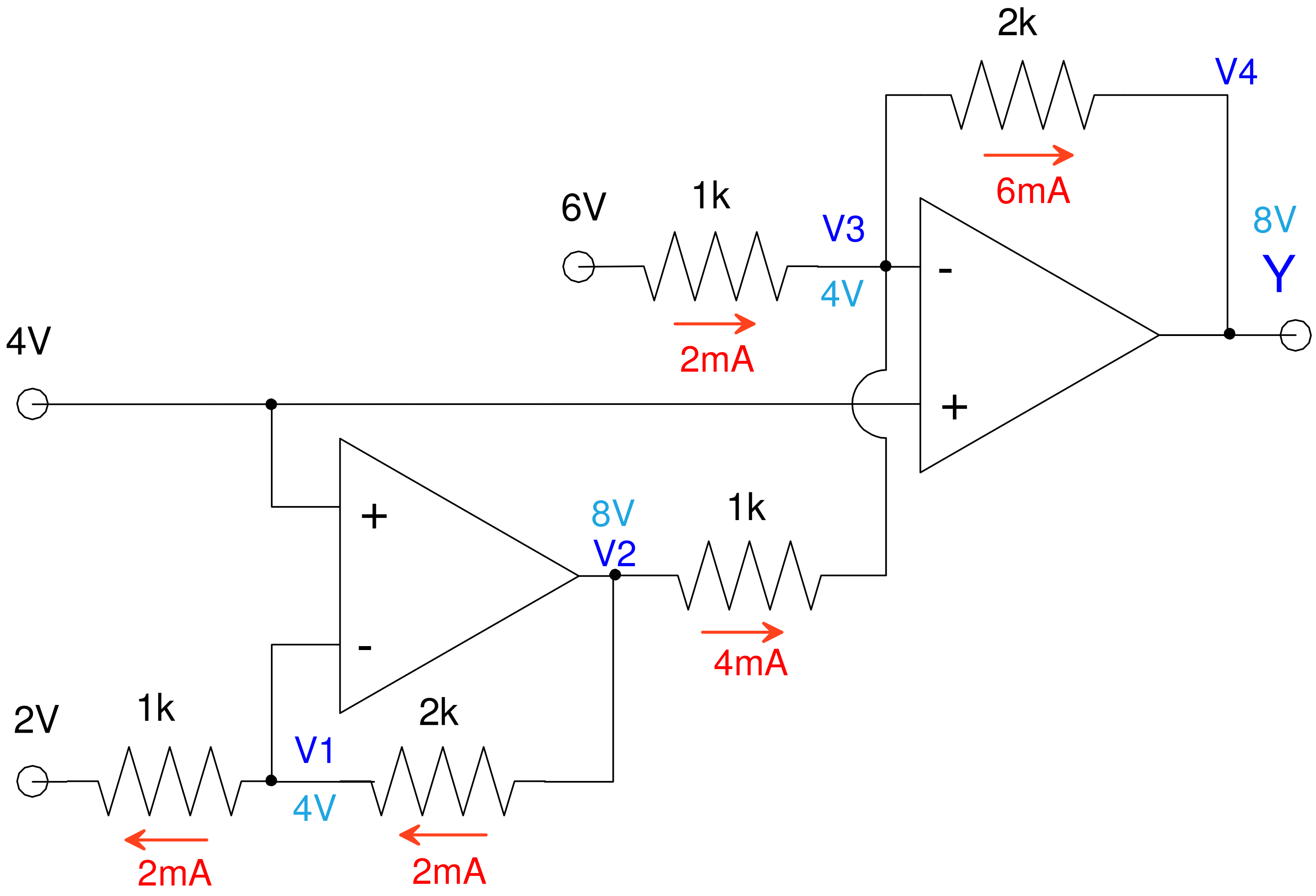
```
V(V1)      4.000 V
V(V2)      8.000 V
V(V3)      4.000 V
V(V4)     -8.000 V
```

# Determine the voltages and currents (take 2)

- Use conservation of current
- (handout problem #1)

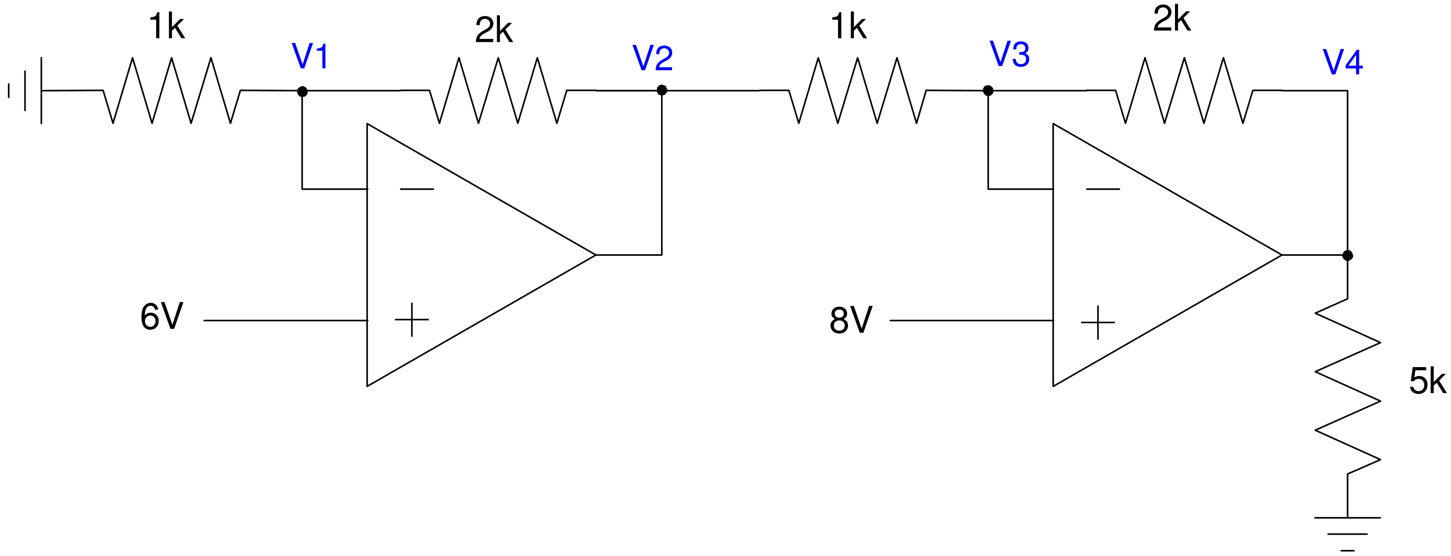


# Solution

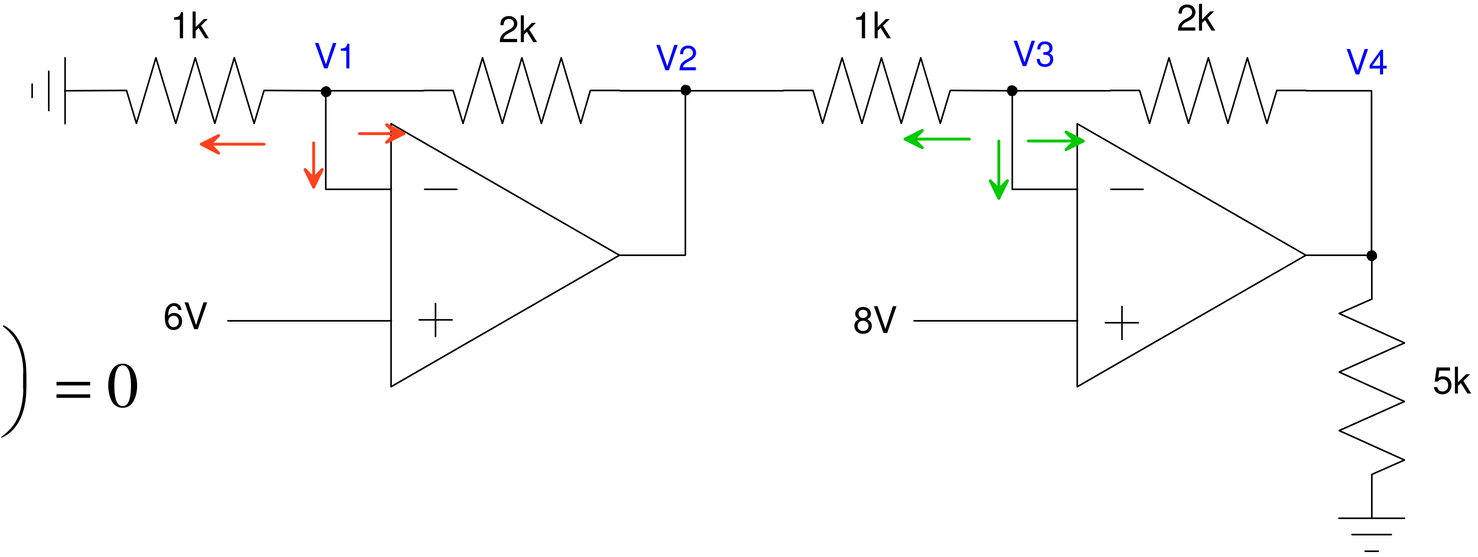


# Example 2: Write the voltage node equations

- 4 equations for 4 unknowns
- (handout problem #2)



# Example 2: Solution



Vp = Vm

$$V_1 = 6V$$

$$V_3 = 8V$$

Node 1 (red)

$$\left(\frac{V_1}{1k}\right) + 0 + \left(\frac{V_1 - V_2}{2k}\right) = 0$$

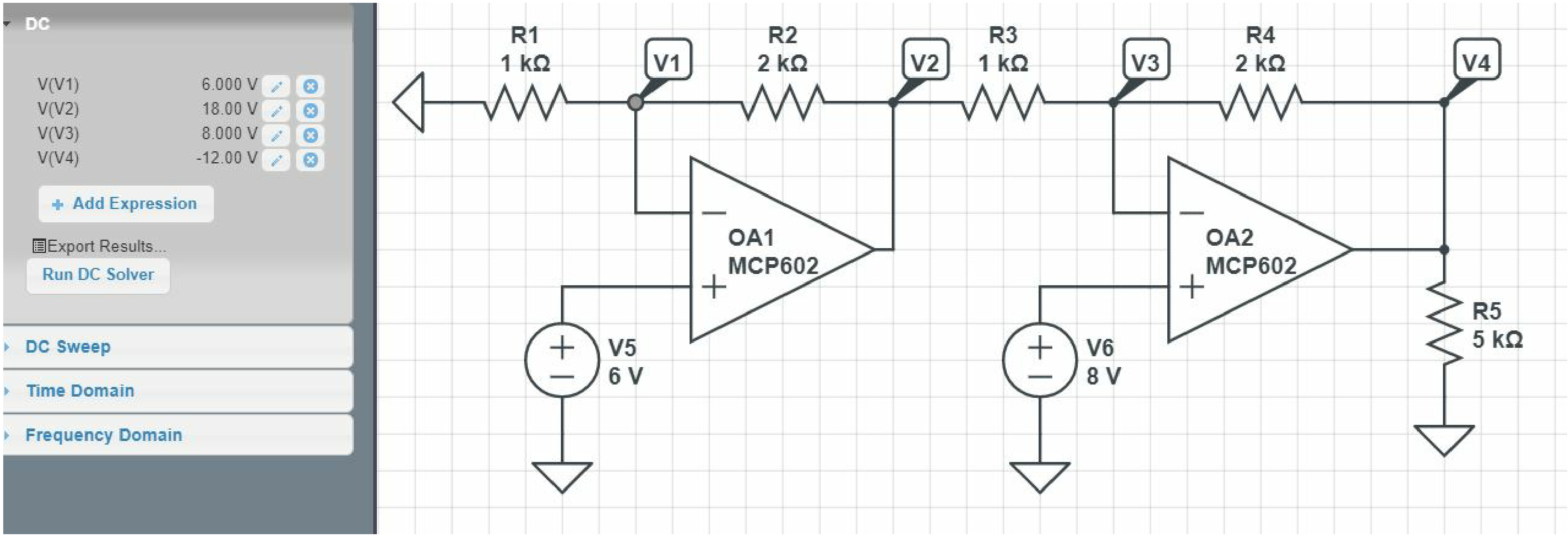
Node 3 (green)

$$\left(\frac{V_3 - V_2}{1k}\right) + 0 + \left(\frac{V_3 - V_4}{2k}\right) = 0$$

Solve in Matlab

```
V1      6.000
V2     18.000
V3      8.000
V4    -12.000
```

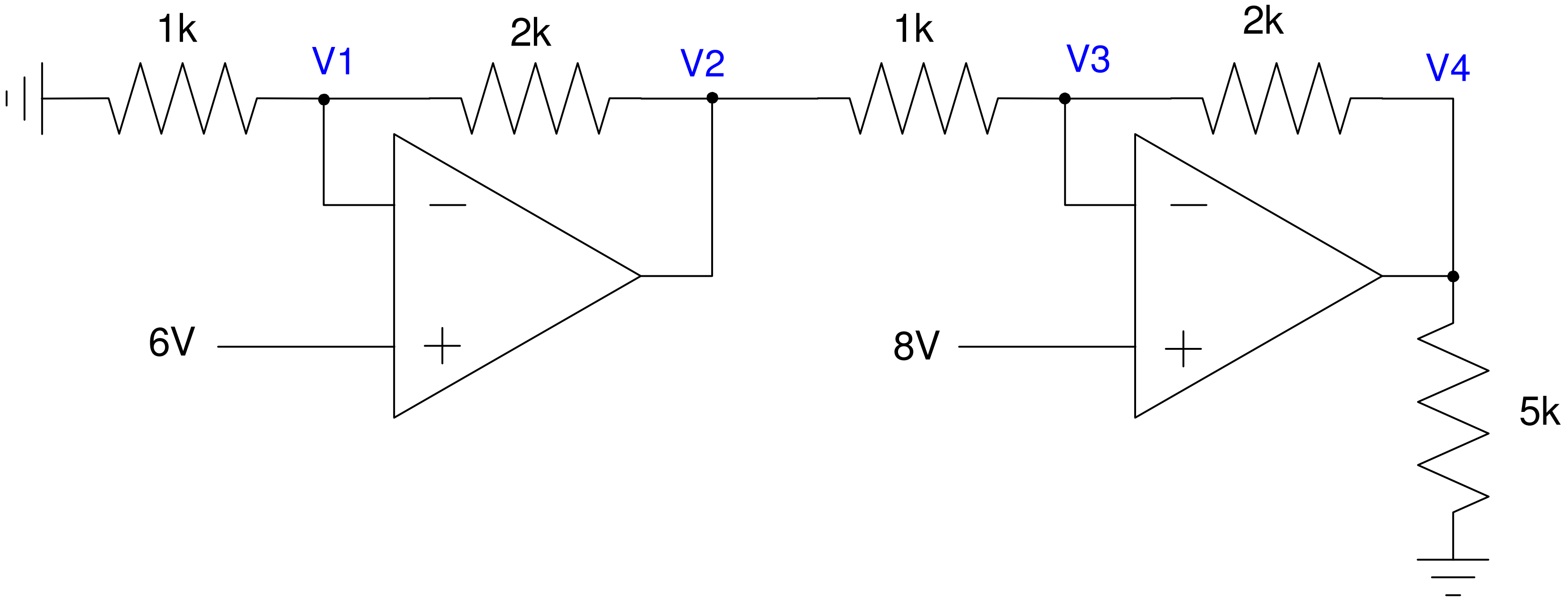
# This checks with the CircuitLab



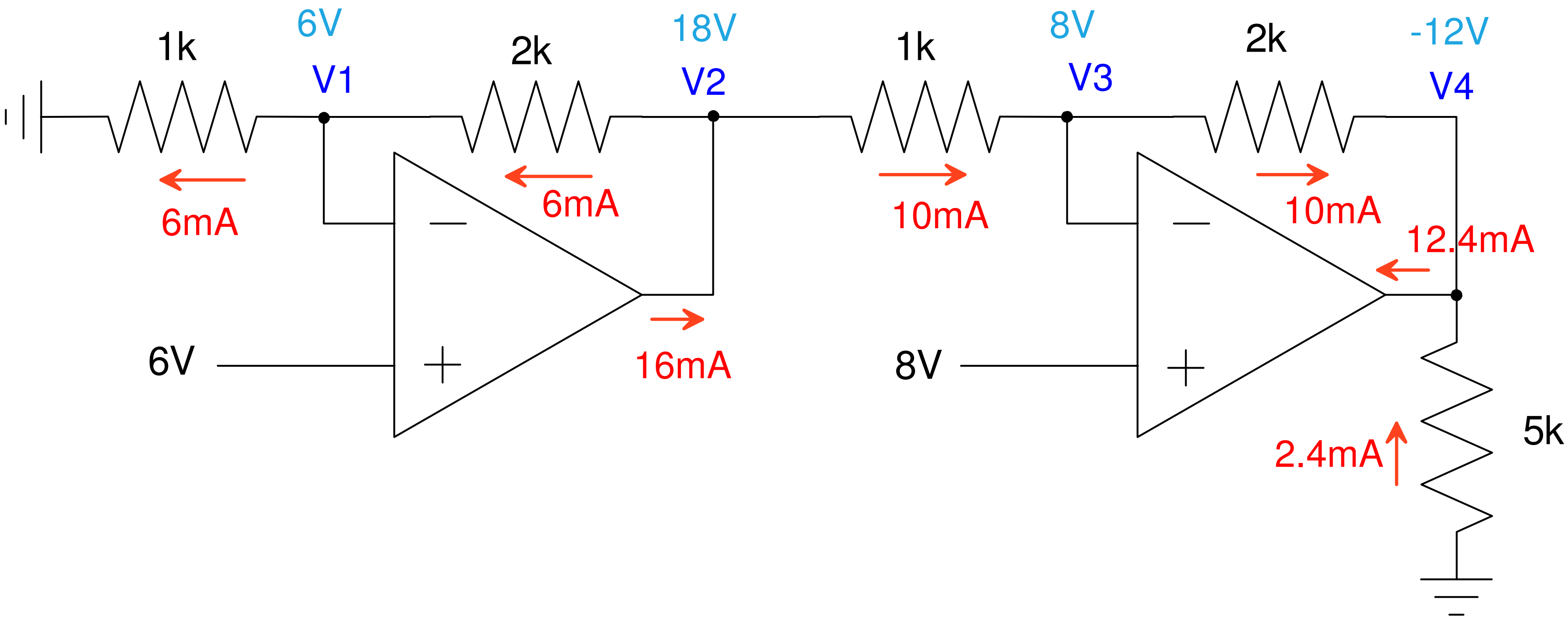
```
V(V1)     6.000 V
V(V2)     18.00 V
V(V3)     8.000 V
V(V4)    -12.00 V
```

# Example 2: Determine the voltages and currents

- Use conservation of current



# Solution:



1k
6V
V1
2k
18V
V2
1k
8V
V3
2k
-12V
V4
6mA
6mA
10mA
10mA
12.4mA
16mA
6V
8V
5k
2.4mA

# Note:

- You don't need to use the op-amps with the +/- power supplies
  - For analog circuits, the output should be finite
  - As long as the power supply allows this, the power supply doesn't matter.
- Using the wrong op-amp (TL081 instead of an LM833) is also OK.
  - They both behave like an ideal op-amp (and likewise have almost identical results).

# Summary

Ideal Op-Amp Model is very close

- Keep $100 < R < 10M$

Voltage Nodes works for op-amp circuits

- For analog circuits, $Vp = Vm$

You can also solve for voltages and currents using conservation of current